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HALOS OF SPIRAL GALAXIES. II. HALO METALLICITY-LUMINOSITY RELATION[1]

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ABSTRACT

Using the Hubble Space Telescope, we have resolved individual red-giant branch stars in the halos of eight nearby spiral galaxies. The fields lie at projected distances between 2 and 13 kpc along the galaxies' minor axes. The data set allows a first look at the systematic trends in halo stellar populations. We have found that bright galaxies tend to have broad red-giant branch star color distributions with redder mean colors, suggesting that the heavy element abundance spread increases with the parent galaxy luminosity. The mean metallicity of the stellar halo, estimated using the mean colors of red-giant branch stars, correlates with the parent galaxy luminosity. The metallicity of the Milky Way halo falls nearly 1 dex below this luminosity-metallicity relation, suggesting that the halo of the Galaxy is more the exception than the rule for spiral galaxies; i.e., massive spirals with metal-poor halos are unusual. The luminosity-halo stellar abundance relation is consistent with the scaling relation expected for stellar systems embedded in dominant halos, suggesting that the bulk of the halo stellar population may have formed in situ.

Subject headings: galaxies: formation – galaxies: halos – galaxies: stellar content –galaxies: individual (NGC 55, NGC 247, NGC 253, NGC 300, NGC 3031, NGC 4244, NGC4945, NGC 5248)

1. INTRODUCTION

It was one of the early studies of the Milky Way's stellar halo that led to the seminal paper on galaxy formation by Eggen, Lynden Bell, & Sandage (1962). It is not surprising that subsequently, thinking about the formation of stellar halo populations has been significantly driven by investigations of the abundances and kinematics of Galactic halo stars, for which such a wealth of information is available. With a wealth of data on kinematics, chemistry, and ages, a picture is emerging in which the Galactic halo is a mix of stars formed very early in the Galaxy's formation history and stars formed later in dwarf galaxies that were subsequently accreted. We do not know the relative balance of these processes, and we do not know whether the early epoch of halo formation was simply a time of more rapid galaxy infall or something more akin to a single starburst.

While we cannot obtain the same amount of information on the halos of other galaxies, it is possible to resolve stars in the halos of nearby spiral galaxies and investigate trends. Do all spiral galaxies have halos? Are they metal poor or metal rich? How do the properties of the stellar populations correlate with other properties of the galaxies?

The only other spiral galaxy in which the stellar halo has been resolved and studied in comparable level of detail to our own Galaxy is the other massive spiral galaxy of the Local Group, M31 (Mould & Kristian 1986; Christian & Heasley 1991; Durrell et al. 1994; Rich et al. 1996; Holland et al. 1996; Ferguson et al. 2002; Brown et al. 2003). The main conclusion drawn from the comparison of the Milky Way and M31 is that the halos of the two galaxies are very different. While the globular cluster systems in both the Milky Way and M 31 halos have similar metallicity distribution functions with equivalent mean metallicities ([Fe/H]≈ -1.6 dex; Huchra et al. 1991; Harris 1996), the metallicity distribution function of field halo stars in M31 is dominated by stellar populations considerably more metal-rich ([M/H]~ -0.5; Mould & Kristian 1986; Durrell et al. 2001) than observed for the Galaxy field halo stars, where the metallicity distribution peaks at [M/H]~ -1.5 (e.g., Ryan & Norris 1991). Clear indications exist that the halo of M 31 underwent more chemical enrichment than did the Milky Way halo (Rich et al. 1996; Durrell et al. 2001). The surface luminosity distribution of the M31 stellar halo follows the de Vaucouleurs law, $R^{1/4}$ (e.g., Pritchet & van den Berg 1994) out to 20 kpc, and a R^{-2} projected profile at larger distances (Guhathakurta et al. 2005; Irwin et al. 2005), in contrast with the surface density distribution in the Galaxy halo that follows $\rho \sim R^{-3.5}$ (Preston et al. 1991, Chiba & Beers 2000; Vivas et al. 2001). Furthermore, the mean density of M31's stellar halo appears to be much higher than that of the Galactic halo (Reitzel et al. 1998). Finally, the M 31 halo shows evidence for a significant intermediate-age population, with over half of the stars at high metallicities ([Fe/H]> -0.5) and intermediate ages of 6–11 Gyr (Brown et al. 2003), in striking contrast to the ancient metal-poor halo of the Milky Way. It is not clear how these differences may be related to different halo formation histories, and/or to different initial conditions in the protogalaxies. We do not know whether the properties of the Milky Way halo are the rule or the exception for spiral galaxy halos.

A key quantity that helps disentangle the formation history of the stellar halo is the galactic halo stellar metallicity. Spectroscopy of giant stars in halos is difficult and

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time consuming, even for stars within the halos of Local Group galaxies (see Reitzel & Guhathakurta 2002 for the first spectroscopic observations of giant stars in M31 halo). Fortunately the colors of red giant stars on the color-magnitude diagram are predominantly sensitive to metallicity rather than age, so a first-approximation estimate of the stellar metallicity can be derived through stellar photometry.

Our knowledge of the metallicities of stellar populations in the outskirts of galaxies is improving rapidly thanks to wide field cameras on the ground and sensitive observations with HST. For the handful of galaxies studied to date, the halo stellar populations are generally higher in metallicity than the Milky-Way halo. Early imaging in the M31 halo by Mould & Kristian (1986) revealed a metal rich red giant branch. The high resolution imaging capability of HST made more halo populations accessible: Soria et al. (1996) and Harris & Harris (2000) find a wide metal rich giant branch in NGC 5128, and Elson (1997) measured a wide and metal rich giant branch in the halo of NGC 3115. Even in the dwarf galaxy NGC 147 a wide and relatively metal rich red giant branch is seen (Han et al. 1997). Yet up to now, no systematic survey has been undertaken using HST to characterize the properties of Galactic halo field stars as a function of parent galaxy properties.

Using photometry of resolved giant stars in the halos of a sample of edge-on spiral galaxies, we obtain the red giant branch locus and thence an inference on metallicity. We report the discovery of a scaling relation between the mean stellar metallicity of halo field stars and the luminosity of the host galaxy.

2. THE DATA

The galaxy selection criteria, observations, and the reduction techniques applied to our sample of highly inclined spiral galaxies are described by Mouhcine et al. (2005a). The locations of the observed halo fields, superimposed on the Digitized Sky Survey images of these galaxies, are shown in paper I and paper III of this series. The integrated magnitude, the foreground extinction-corrected $(J-K)_{\circ}$, and the distance modulus of the galaxies in our sample are listed in Table 1 (see paper III of this series for more details on the adopted distance moduli for the sample galaxies). Extinction- and inclination-corrected V-band magnitudes come from de Vaucouleurs et al. (1991; RC3). The infrared photometry is taken from the Two Micron All-Sky catalogue (Jarret et al. 2000). No significant internal extinction is expected to affect the halo stellar populations, as halo regions are most likely dust free. The reddening toward each halo field was estimated using the all-sky map of Schlegel et al. (1998). The images are sufficiently deep to reveal RGB stars with roughly a solar metallicity in almost all the observed fields, but in some cases it requires careful modeling of incompleteness to characterize the high-metallicity end. Fig. 1 shows the completeness levels as a function of I-band magnitudes for the observed halo fields, determined from artificial-star experiments (see paper III of this series for more details on artificial star experiments and completeness levels of the data). The completeness levels are shown for the particular colors (V-I)=1.4 (left panel) and (V-I)=2.35 (right panel). Due to observing time constraints, the depths of the images vary from galaxy to galaxy, with 50% completeness limits ranging from absolute magnitudes −0.9 to −3.5.

Our use of the term "halo" throughout this paper is necessarily imprecise. While our fields are projected along the minor axes well outside the visible outskirts of the disks and bulges on the Palomar Sky survey, there may nevertheless be some bulge, disk and/or thick disk stars in our fields. It might be possible to quantify the possible contribution of these components by fitting parametric models to deep near-infrared surface photometry, but we do not have such data for the full sample, and the definition would be largely rely on the extrapolation of these parametric fits well beyond where they are constrained by photometry. We note that even in the well-studied case of M31, where the outer galaxy can be studied by counting stars, it is difficult to define where the bulge or disk ends and the halo begins. Thus when we refer to "halo" we simply mean "stars along the minor axis, well outside the visible bulge and disk."

3. HALO STELLAR METALLICITY-LUMINOSITY RELATION

A detailed discussion of the color-magnitude diagrams of our sample galaxies is presented in Mouhcine et al. (2005b), to which the reader is referred. The halo stellar populations of spiral galaxies are found to be dominated predominantly by red giant stars, indicating stellar populations older than 1 Gyr (e.g., Sweigart, Greggio, & Renzini 1990). It is well known that the colors of giant stars in an old simple stellar population are mainly affected by the abundances of heavy elements and only to a much smaller extent by the age of the stellar population. For example, at $M_I = -3$ on the red giant branch, a 0.2 mag shift in $V-I$ to the blue can be achieved by a relatively large decrease in age from 13 to 6 Gyr or a relatively small decrease in [Fe/H] from −1 to −1.2. Thus, at a given luminosity, redder stars are generally more metal-rich than bluer ones, and the width of the red giant branch at a given luminosity is an indicator of the spread in the stellar metallicity. Fig. 2 shows the incompleteness- and foreground-extinction corrected color distributions of red giant branch stars within the magnitude range $-3.5 \leq M_I \leq -2.5$ for the galaxy sample ranked by luminosity.

Our photometry for NGC 4258 does not reach as deep relative to the RGB tip as it does in other galaxies in the sample. It is clear from the photometry at the bright end of the RGB that the metallicity distribution is broad and extends to high metallicity. However, the 50% completeness level is sufficiently bright (see Fig. 1) that it makes our interpretation of the high-metallicity end of the distribution highly uncertain. The effect of incompleteness was included in our construction of the color distribution to the best of our ability, but the corrections become large and uncertain at the highest metallicities. If we have underestimated our incompleteness, the color distribution for NGC4258 would move to the red and the width would broaden. Further deep observations in the optical and near-IR of this galaxy are clearly warranted. However, we should mention that the conclusion drawn in this paper do not rely on NGC 4258.

Considering the color distribution of giant stars alone, two striking properties emerge. First, the mean color tends

to be redder for brighter galaxies, and second, the width of the color distribution tends to be wider for brighter galaxies. We see no evidence for bi- or multi-modality in the color distribution of giant stars; however this does not necessarily mean that the metallicity distributions are unimodal, because the relation between the color and metallicity of giant stars is nonlinear.

Once the stellar photometry is extinction- and distance-corrected, we can estimate the mean metal abundances via a comparison with the fiducial globular cluster giant branches. Lee et al. (1993) have provided a quadratic abundance calibration based on the mean $(V-I)_{\circ}$ color of the red giant branch at a luminosity of $M_I = -3.5$ for the full abundance range of the calibration clusters ($-2.2 \leq$ [Fe/H] ≤ -0.7). Adopting $M_I = -3.5$ mag as a reference for the abundance determination increases the sensitivity to abundance, minimizes the influence of asymptotic giant branch stars, and also reduces the effect of photometric errors in most cases. Metal-rich stars, i.e., [Fe/H] $\gtrsim -0.5$, lie below $M_I = -3.5$. No calibration of the relationship between stellar metallicity and (V-I) color at a fainter absolute I-band magnitude is available for such metallicities. If metal-rich stars are present in the halos of spiral galaxies, they will be not taken into account to calculate the mean stellar halo metallicity using Lee et al. (1993) calibration, and then possibly biasing the estimated metallicities toward low metallicities. However, the color-magnitude diagrams of the observed halo field, presented in paper III of this series, show that while a metal-rich stellar population is present, it is not dominant (see paper III of this series for a detailed analysis of the metallicity distribution functions for the galaxy sample). Thus we do not expect any significant bias toward low metallicities. To measure the $(\mathrm{V}-\mathrm{I})_{\circ,-3.5}$, we calculate the histogram of the colors of stars within $M_I = -3.5 \pm 0.1$. To determine the uncertainties, we carry out a bootstrap resampling procedure. For each simulated sample, the histogram of stellar colors is fitted by a Gaussian. We then fit a Gaussian to the final distribution of $(\mathrm{V}-\mathrm{I})_{\circ,-3.5}$ for the simulated samples, and use its mean and dispersion as the best estimate of $(\mathrm{V}-\mathrm{I})_{\circ,-3.5}$ and its uncertainties. We have repeated the same procedure using the median value for the simulated samples instead of the peak of the Gaussian, or using a mean value of simulated samples means, and the differences never exceed 0.02 dex. The estimated mean $(\mathrm{V}-\mathrm{I})_{\circ,-3.5}$ color for the observed halo field of NGC 4945 is slightly redder than the color of the most metal-rich globular cluster used to calibrated the $(\mathrm{V}-\mathrm{I})_{\circ,-3.5}$ vs. [Fe/H] relation, but still consistent within the errors. To estimate the mean stellar halo metallicity for NGC 4945, we have simply extend Lee et al. (1993) calibration to the observed mean $(\mathrm{V}-\mathrm{I})_{\circ,-3.5}$ color.

Note that because of the low completeness level at $M_I = -3.5$ mag for NGC 4258 halo red stars, i.e., $(\mathrm{V}-\mathrm{I}) \gtrsim 2$, we are possibly missing a fraction of metal-rich/red stars. The mean $(V-I)_{\circ}$ color of halo red giant branch stars at a luminosity of $M_I = -3.5$ for this galaxy might be biased toward a bluer color. The estimated mean metallicity of NGC 4258 halo stars might be then underestimated. The errors are the formal errors of the mean; the overall uncertainty in the mean metallicities is conservatively estimated to be ± 0.3 dex because of systematic errors in the photometry and/or the calibration. In paper III, we compute metallicity distributions by applying corrections star by star and obtain consistent results.

Fig. 3 shows the variation of the mean abundance of the halo field stars as a function of the absolute V-band magnitude of the parent galaxy for our galaxy sample. In order to examine the luminosity-stellar halo metallicity relation over a large range of luminosity and metallicity, we have augmented our database of halo field star mean abundances with published measurements for galaxies observed to sufficient depths to measure securely the halo star abundances. We have overplotted the values of the stellar halo abundances of M 31, the Milky Way, the giant E/S0 NGC 5128, and the S0 galaxy NGC 3115. All investigations of the M 31 stellar halo, following the pioneering work of Mould & Kristian (1986), find the dominant field population has a mean metallicity of around [Fe/H] ~ -0.8 dex, over a wide range of projected distances from ~ 5 kpc to ~ 30 kpc (Rich et al. 1996; Holland et al. 1996; Durrell et al. 2001, 2004; Bellazzini et al. 2003). A large observational effort was dedicated to investigate the abundance distribution of the Galaxy halo. Both kinematically selected (Laird et al. 1988; Ryan & Norris 1991) and non-kinematically selected (Beers et al. 2000) halo star samples show that the metallicity distribution function peaks at [Fe/H] ~ -1.5 dex. The galaxy luminosities are taken from the Local Group catalog of van den Bergh (2000). Harris & Harris (2000, 2002) have shown that the stellar halo of NGC 5128 is dominated by a metal-rich component extending to a solar metallicity with a mean metallicity of [Fe/H] ≈ -0.7 dex. Kundu & Whitmore (1998) have reanalyzed deep imaging data for NGC 3115 from Elson (1997), and published the color distribution of bright halo giant stars. Using a distance modulus of $(m-M)_{\circ} = 30.2$, fitting a Gaussian to the color distribution in the magnitude range $-3.7 < M_I < -3.5$ (as given in Kundu & Whitmore 1998), and converting the mean color to a mean metallicity using Lee et al. (1993) calibration, we found that the mean halo metallicity is $[Fe/H] \approx -0.7$. The metallicity of the stellar populations in the outer parts of M 33 have been measured. However, we have not included M 33 to define the stellar halo metallicity-luminosity relation, as it is not clear to which galactic component, i.e., galactic disk or stellar halo, stars in the outer parts of M 33 belong to. Mould & Kristian (1986) have found that the stellar halo of M 33 is dominated by metal-poor stars, i.e., [Fe/H] ~ -2 dex, with a small spread. Tiede et al. (2004) have imaged a field in the outer part of M 33 including the Mould & Kristian (1986) field but find [Fe/H] ~ -1 and an age gradient. They argue that they are in fact imaging the outer disk of M33 (see also Brooks et al. 2004 for similar results). The metallicity gradient within their observed field is consistent with the spatial variation of stellar metallicity seen in the inner disk regions of M 33, suggesting that the majority of stars in their field belong to the disk, not the halo (Tiede et al. 2004). Recent observations show that stars in the outer parts of M33 are distributed exponentially as within discs (R. Ibata, private communication). The outer part of M33 seems to be dominated by disk stars rather than halo stars. Most of the galaxies in our sample with types and luminosity similar to M33 are highly inclined (apart

from NGC 300). Thus our fields are much more likely to be dominated by halo stars than any field yet observed in M33. Fig. 2 shows that a good correlation is present in the data between the parent galaxy luminosity and the mean abundances of field halo stellar populations.

For comparison, the dashed line indicates the scaling relation, $L \propto Z^{2.7}$, expected for objects originating as gaseous protogalaxies embedded in dominant dark matter halos framed within the context of a single star formation event, and whose the chemical enrichment was dictated by enrichment from massive stars and gas loss via supernovae-driven winds under the assumption of instantaneous mixing (Dekel & Silk 1986). The slope of the predicted luminosity-metallicity relation is based on the key assumption that the galactic objects are embedded in dominant dark matter halos. Note the arbitrary metallicity zero point of this relation.

Surprisingly enough, both early type galaxies, i.e., NGC 5128 and NGC 3115, fall on the relation defined by spiral galaxies, suggesting that the diffuse halo stellar populations in elliptical galaxies may share some similarities with spiral halo stellar populations. One possibility is that in most cases we are observing the outer extensions of the bulge/spheroid. One may also consider the possibility that giant early-type galaxies might have experienced a chemical enrichment and star formation history in their outer regions similar to that seen in the halos of typical bright spiral galaxies. Larsen et al. (2001) have recently analyzed the properties of globular cluster systems around a large sample of early-type galaxies, and their correlations as functions of the parent galaxy properties. They concluded that the data appear to favor a scenario where globular cluster systems as a whole form in situ after the elliptical progenitor has been assembled into a single potential well. In both scenarios, where halo globular clusters and field stars form roughly contemporaneously, or where halo field stars are the results of tidal stripping of the globular clusters, one may expect that field halo stellar populations in ellipticals should obey the luminosity-halo stellar abundance relation of spiral galaxies. Harris & Harris (2000, 2002) have shown that it is unlikely that halo of NGC 5128 was built by accretion of pre-existing, gas-free small satellite galaxies, and favor an in situ formation model where the star formation proceeds in two stages. To investigate in more detail the similarities between spiral galaxy halos and early-type galaxy halos, data of the necessary depth for other normal elliptical galaxies, such as NGC 3379, are needed.

The most striking result from the figure is that the mean metallicity of the Milky Way stellar halo does not fit onto the luminosity-halo stellar metallicity relation, lying low by an order of magnitude. This suggests that the stellar halo of the Galaxy *may not be typical for a normal spiral galaxy of its luminosity*, i.e., galaxies with luminosities similar the Galaxy luminosity clustered at $[Fe/H] \sim -0.7$ compared to $[Fe/H]_{MW} \sim -1.6$. Clearly a larger sample is needed to determine what parameters, other than total luminosity, correlate with halo metallicity.

Recently, Bekki et al. (2003) have investigated numerically the physical processes that may produce the observed metallicity distribution function of NGC 5128, considering a model in which the galaxy has been formed by the merging of two spiral galaxies. One of the key inputs of their simulations is the metallicity distribution of the stellar halo of a merger progenitor spiral. They consider that the field halo stellar population of a typical spiral galaxy is similar to what is observed for the Galaxy, in contradiction with our finding. To populate the halo of the merger product with metal-rich stars, as is observed for NGC 5128, their models require that the stellar halo be composed of stars that were located in the outer parts of the two merging disks as they were tidally stripped during the merging event. If halos are in general more metal rich, it might make this model less tenable.

The figure shows that all of the sample galaxies fall along the $L \propto Z^{2.7}$ scaling relation. Unfortunately, the sample galaxies clustered into two clumps. Intermediate luminosity galaxies, i.e, $M_{V,\circ} \sim -20$, are missing in our sample, so we cannot draw a firm conclusion about their location in the stellar halo luminosity-metallicity relation. Furthermore, galaxies brighter than the brightest in our sample are suspected to behave differently. Indeed, Kauffmann et al. (2003) have shown that galaxy properties change dramatically at stellar masses of $\sim 3 \times 10^{10} M_{\odot}$; galaxies with stellar masses above this limit have a larger fraction of old stellar populations, and concentrations typical of bulges, while galaxies with lower stellar masses are dominated by relatively young stellar populations and have low concentrations typical of disk galaxies. This behavior contrasts with the evolution of dark matter halo properties, which should vary smoothly with mass. It will be important to measure the metallicities of halos of galaxies with intermediate luminosities to further explore the connection between halos and their parent galaxies. Nevertheless, the apparent fact that stellar halos follow a luminosity-metallicity relation similar to what is predicted for gas clouds embedded in massive halos is consistent with a halo formation scenario where field stars formed in the virialized potential well of the parent galaxy. As mentioned in the introduction, it is likely that our fields contain a mix of stars traditionally associated with halo, bulge and thick disk. Some of the galaxies in our sample have prominent bulges (e.g. NGC 4258 and NGC 4945), and it is possible that our stellar samples in these galaxies are dominated by the extension of the bulge component. The contribution of bulge stars could bias the mean stellar halo metallicity toward higher metallicities. If this is true, the variation of galaxy properties, e.g., bulge-to-disc ratio, at a given galaxy luminosity might produce a variation of mean stellar halo metallicities for galaxies with similar luminosities. The observed kinematics of M 31 halo stars support this possibility. Indeed, they are rapidly rotating similar to the M 31 bulge (Hurley-Keller et al. 2004; see Perrett et al. 2002 for a similar result for the kinematics of globular cluster system around M 31). Thus our observed halo metallicity-luminosity relation could be indicating the trend for more luminous galaxies to have more prominent bulges. It is unclear how this relates to the merger vs. in-situ star-formation scenarios, since both bulges and halos can grow by either process. A key test will be to obtain metallicities of extra-planar stars in massive late-type (e.g. Sc) galaxies without prominent bulges.

Alternatively, halos may form primarily by the disruption of relatively gas-free dwarf galaxies orbiting around

the parent galaxy. If the stellar halos were formed hierarchically from the disruption of dwarf galaxies, one might expect that the stellar halo of brighter galaxies may be dominated by metal-rich stars as the mass function of galactic satellites around bright galaxies might extend to larger masses. Unfortunately, the slope of the metallicity-luminosity relation in such scenarios is not easily predictable, and may depend on a large number of unknown ingredients, e.g., dwarf galaxy mass function, feedback at low mass scale, and the detailed merging history. It will require more detailed modeling to determine whether a pure accretion model such as this can be ruled out.

Fig. 4 shows the evolution of the halo field star mean metallicity as a function of the integrated foreground extinction-corrected near-infrared color $(J-K)_\circ$. The stellar halo mean metallicity correlates with the parent galaxy color. Taken at face value, this may indicate that the star formation and chemical evolution histories of both the stellar halo and the body of the parent galaxy may be connected. This comes as a surprise, since, as it is well established, disk galaxies are, generally speaking, still actively forming stars, while stellar halos are not. What may cause a connection between the halo metallicity and the parent galaxy color? For the galaxy sample, augmented by data from the literature, $(J-K)_\circ$ correlates with the galaxy luminosity as shown in Fig. 5, with rather a large scatter. Combined with Fig. 3, the apparent correlation in Fig. 4 is driven by the color-magnitude correlation of the sample galaxies. The sample galaxies also follow an optical-infrared color-magnitude relation.

It is well-established that early-type galaxies obey a tight color-magnitude relation (de Vaucouleurs 1961, Sandage & Visvanathan 1978, Bower et al. 1992). This correlation is generally understood as a change in metallicity as the galaxy mass increases, i.e., a metallicity-luminosity sequence (Vazdekis et al. 2001). A similar relation is observed for spiral galaxies (Tully et al. 1982; Wyse 1982). This is generally interpreted as a combined effect of increasing metallicity (Bothun et al. 1984), and/or of a decreasing fraction of blue stars (Peletier & de Grijs 1998) with increasing galaxy mass, with no clear sensitivity to the Hubble type (Gavazzi 1993). The issue is still a matter of debate, because of the effects of both complex star formation and chemical evolution histories for spiral galaxies, as well as the internal reddening (see Arimoto & Jablonka 1991 for a discussion).

The $(J-K)_\circ$ vs. M_H relation for our sample is in good agreement with the disk dominated spiral galaxy relation presented by Bothun et al. (1984). Bright galaxies are expected to be more affected by internal reddening than fainter ones (Jansen et al. 2001; Mouhcine et al. 2005c). For the sample galaxies, the change of infrared colors with absolute magnitude is small, and differential reddening of $\delta E(B-V) \sim 0.3$, can account for a color offset of $\delta(J-K) \sim 0.2$, similar to what is observed. The short baseline of infrared colors does not allow a good continuum definition. The color-magnitude relation shows up again in the optical-infrared regime: the (V-K) color is bluer for fainter galaxies, in a sense that cannot be account for by a simple differential reddening between faint and bright. So, the galaxy mass/luminosity regulates, in broad terms, the stellar content of spiral galaxies. Thus the correlation seen in Fig. 4 between the halo field star mean metallicity and the galaxy color is not indicative of any fundamental evolutionary link between the halo and the galaxy disk, other than the fact that the evolution of both disk and halo stellar populations is dominated by the galaxy luminosity.

4. SUMMARY & CONCLUSIONS

Using a data set from HST imaging of spiral galaxies, we have shown that the colors of halo red-giant branch stars correlate with parent galaxy luminosity. As galaxy luminosity increases, the color distribution broadens and the peak moves to redder colors. We have interpreted this trend in color as a trend in the mean metallicity of the halo populations, using color-metallicity relations calibrated on the Galactic globular clusters, and find that the mean abundance of halo field stars correlates with the galaxy luminosity. Galaxies with accurate determinations of the stellar halo mean abundances follow the new luminosity-metallicity relation, with the exception of the Milky Way halo, which is almost an order of a magnitude more metal-poor than galaxies with similar luminosity. Thus the Milky Way may not have a typical halo. Its stellar population differs substantially from those found in the halos of other bright spiral galaxies. Our finding reinforces the view that for large galaxies of all types, moderately metal-rich stellar halos should be the norm, not the exception. The slope of the luminosity-metallicity relation suggests that the bulk of the diffuse stellar halo forms in the gravitational potential of the final galaxy, and was not formed in dwarf-like galaxies that were tidally stripped subsequently.

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Table 1

Basic properties of the sample galaxies. Columns: (1) Galaxy name; (2) Galactic foreground extinction-corrected V-band absolute magnitude; (3) $(J-K)_\circ$ color corrected for Galactic foreground extinction; (4) distance modulus; and (5) mean metallicity of the stellar halo.

Galaxy	M_{VO}	$(J-K)_\circ$	$(m-M)_\circ$	$<[Fe/H]>_{\rm Halo}$
NGC 55	-19.02	0.72	26.11	-1.69
NGC 247	-18.91	0.64	27.30	-1.44
NGC 253	-21.13	1.03	27.59	-0.74
NGC 300	-18.62	0.65	26.53	-1.93
NGC 3031	-21.14	0.89	27.80	-0.90
NGC 4244	-18.96	0.83	27.88	-1.48
NGC 4258	-21.30	0.90	29.32	-0.70
NGC 4945	-20.77	1.02	27.56	-0.66

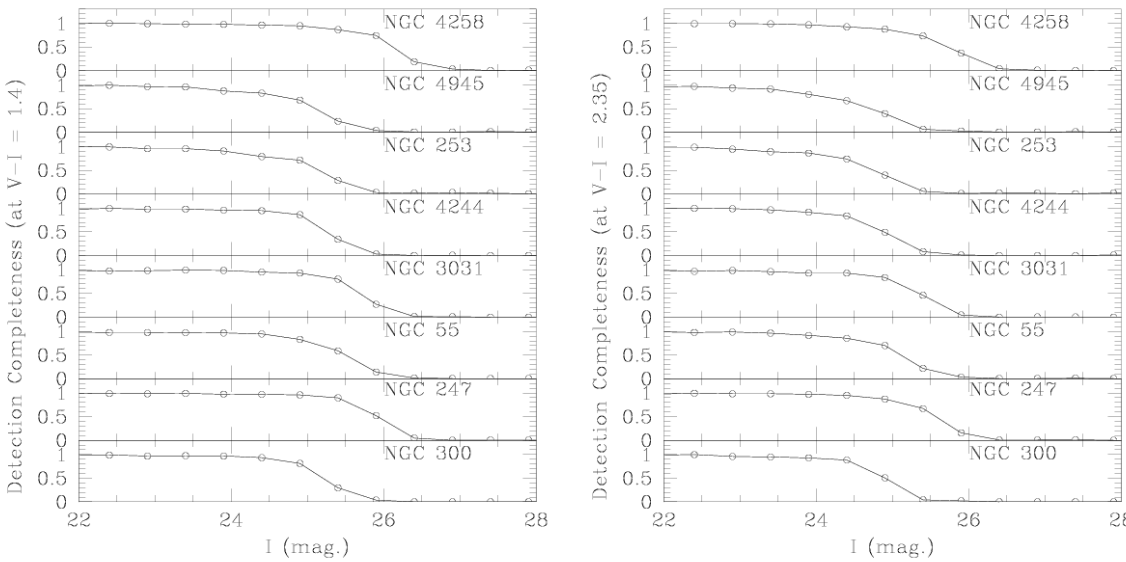

FIG. 1.— Detection completeness as a function of magnitude for each of the WFPC2 fields, as determined from artificial-star experiments, for (V-I)=1.4 (it Left), and (V-I)=2.35 (it Right) respectively.

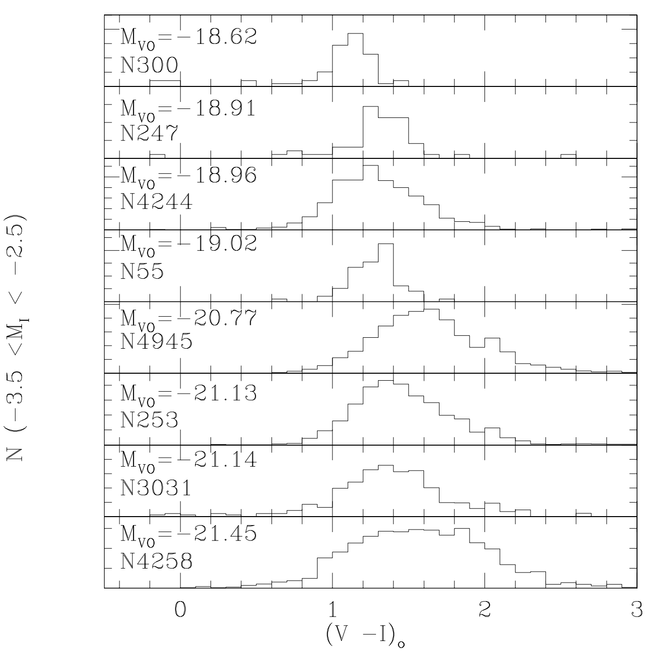

FIG. 2.— Incompleteness- and extinction-corrected color distribution of stars with absolute magnitudes $-3.5 \leq M_I \leq -2.5$.The galaxies have been arranged in order of absolute face-on V-band magnitude, corrected for both Galactic extinction and galaxy inclination.

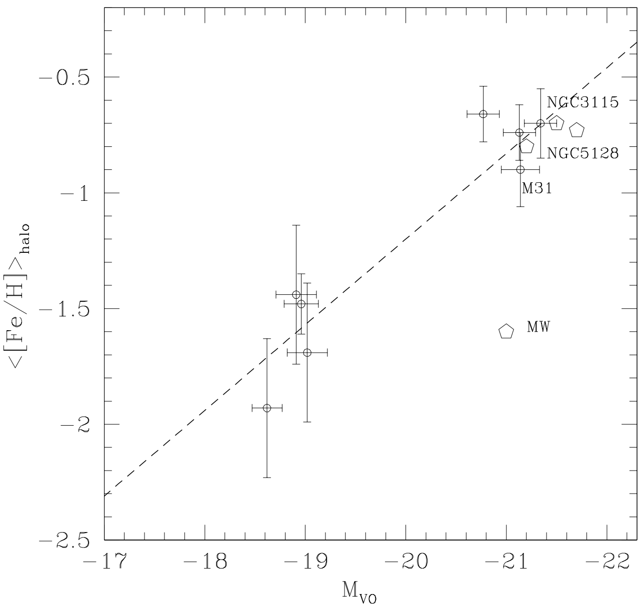

FIG. 3.— Mean metallicity of halo stellar populations plotted against parent galaxy absolute luminosity. Pentagons display data collected from the literature for galaxies named in the figure. MW indicates Milky Way galaxy. The dashed line is a rough fit to the [Fe/H]-M_V relation, $L \propto Z^{2.7}$, similar to the [Fe/H]-M_V relation of Dekel & Silk (1986) for dwarf stellar objects formed in potential wells.

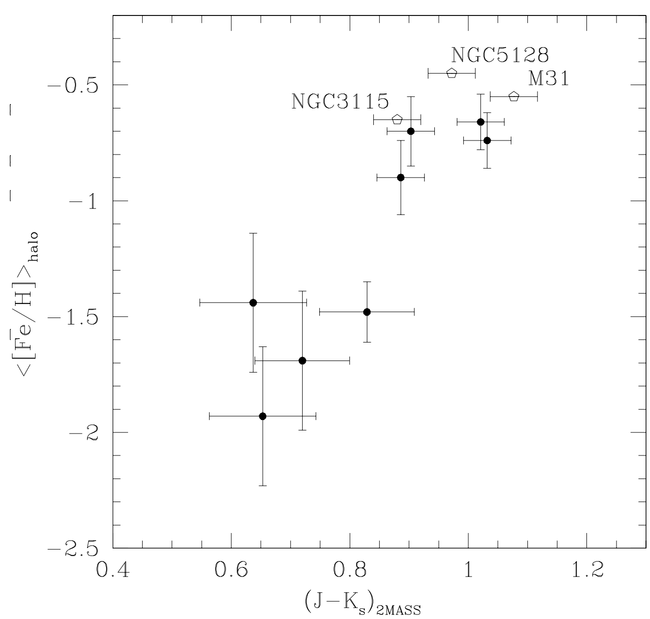

FIG. 4.— Mean metallicity of halo stellar populations plotted against the parent galaxy foreground extinction-corrected (J-K).

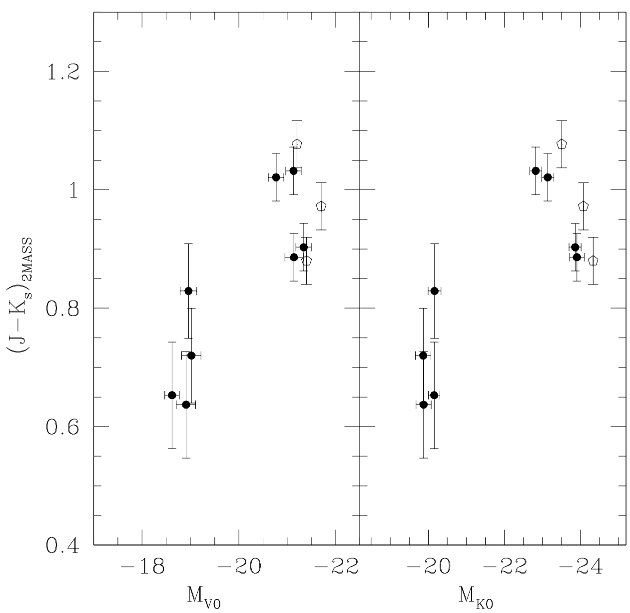

FIG. 5.— Color-magnitude relation for the sample galaxies. The colors are calculated using integrated magnitudes.